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Subject: Coupled Cavity 3-D Codes for Linac Tolerance Simulations.
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Coupled Cavity 3-D Codes for Linac Tolerance Simulations.

Les W. Oleksiuk
Accelerator Division.
Fermilab, Batavia,Ill.

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Abstract: Programs CAVGEN:TRACEX:CAVDYN

Three developing codes, based on previous work at Los Alamos (1) are now being used in the Fermilab Linac Upgrade project, to survey system tolerance requirements .Both linear and non-linear beam dynamics of a pi-mode side coupled 805 MHz linac are simulated. Particular attention to the z-plane synchronism has been integrated into the code group, so that klystron drive boundaries can be monitored in the dynamics. All system length errors that contribute to desynchronization, and other data set failures are recognized by the particle PIC code (CAVDYN) to enhance design coherence.

Some current results of the CAVDYN code simulations will be discussed.

Introduction.

Following parallel to the 3-d PIC codes used for drift tube linac design and simulation (eg. PARMILA), the synthesis, design tuning and dynamics simuiation functions have been developed for the coupled cavity proton linac systems, typically run as pi-mode standing wave structures. These functions have evolved in modular fashion, since, at present the 'CAVGEN' (synthesis),'TRACEX '(linear design tuning), and 'CAVDYN' (non-linear particle dynamics)exist as separate codes. All three codes,because of their independence, have been interfaced to use the TRACE3D data set formats, thus using a common vehicle for system specification. This allows a system design , including linearized space charge, to be checked out, and fine tuned using TRACE3D .A slight modification of the TRACE3D data set is incorporated into the code group, to allow a central orbit monitor function. A development version (TRACEX) of TRACE3D is used to handle the additional tank and bridge coupler synchronization data, imbedded in the i/o data sets.

System Design.

A system layout, using design parameters constrained by the maximum electric fields, rf power allocations and beam size considerations, is generated ('CAVGEN'), using the structure data typically from SUPERFISH cavity designs. These reflect the beam (or travelling wave) velocity dependencies of the structure.

Because of the complex interactions between longitudinal and transvserse planes, caused by the departure from synchronism during a multi-cell cavity transit, the effects of linearized space charge must be added to the system simulation.This is performed by the 3-d linear matrix code TRACE3d (or TRACEX,enhanced.zorbit), which trims both longitundinal and transverse planes for space charge matching.
The trimmed data set is inputted to CAVDYN, which reconstructs the central orbit , recognizing all synchronous constraints implied in the RF (klystron) drive boundaries,and cell-length to tank pair [Wout,phis] correspondences.

The CAVDYN (PIC)code follows the central orbit, independently of the phase space population under study. This allows consistency checks of various features of the system design process.The central orbit designed by 'CAVGEN' is not recognized by TRACEX dynamics. TRACEX simply passes the synchronizing data to the PIC code 'CAVDYN'.
Correct design trimming by TRACEX should not affect this orbit. Inadvertant orbit changes produced by TRACE3D will be picked up by 'CAVDYN'. 'Real' ,as opposed to 'ideal' cavity fields can be placed into the datasets,and the central orbit can be monitored for quantitative estimates of as-built beam behaviour.

Design Process Integrity.

The following features have been identified during the Fermilab Upgrade Design, as being important in establishing design coherence for coupled cavity linacs.All these conventions are maintained by the three codes to assure consistency in the system performance predictions.

(a) All 3 codes use the same gap transformations in the dynamics involving the rf forces. Only the linear portion of these transformations are used in the genlin (CAVGEN) and trace3d (TRACEX) ,while the higher order radial terms are added ,via the 'HIORD' flag in CAVDYN. Transverse-longitudinal terms are implicit in the CAVDYN (PIC) formulation, as additional non-linearities.

Actual gap transformations used are a single transit time parameter, using two half.cell transformations per rf cell. This conforms to the original TRACE3D usage for coupled cavity dynamics in the 'tank' element.
Tests involving mixed usage ,using a single gap transformation in the genlin (CAVGEN), and two half.cell transformations in the both dynamics codes, predicted small z-plane oscillations. These oscillations were removed by small adjustments of the input beam energy, agreeing with systematic error simulations previously reported by a Soviet group (2.).
Thus approximations inherent in the use of gap transformations rather than exact E.O.M. integrations would produced small errors in the input synchronous energy,at the beam energies in this study. Further elaboration of the radial e-field dependencies are under investigation, and are not reported here.

(b) Synchronism is defined as a 'tank' pair, rather than a cell pair, for coupled cavity linacs.
The term 'TANK' as found in the TRACE3D usage,is a set

of n accelerating cells whose standing wave phasors exhibit 180 degrees jumps axially..Implied in this desciption, is the rf pathway provided to support the 180 degree axial phasor pattern, with intermediate offaxis cells introducing 90 degree jumps in the phasor pattern. The term 'CAVITY' and 'TANK' are used interchangably here. All n-axial cells have the same cell-length, providing a travelling wave with a constant phase velocity, which traverses two axial cells per rf period.

An algorithm in 'CAVGEN' determines the 'tank' synchronous pair [Wout,phis], which essentialy predict the state of the synchronous particle at a tank exit plane,as well as the travelling wave velocity within the adjacent drifting region (bridge coupler). CAVGEN thus produces both cell lengths and bridge coupler lengths (constrained to be odd-cell length drifts) that maintain correct rf phase relations during the drifting process.The 'CAVGEN' code defines the 'tank' synchronous condition as two pairs - [wsin,phis] and [wsout,phis], where the entering and exiting phases (phis) are equal. Within the tank the z-orbit phase swings, initially as much as 10 degrees within the 16.cell accelerating cavities generated in the Fermilab 805MhZ Upgrade Linac.

'CAVGEN' generates n-cell cavities , synchronous drifts and non-synchronous drifts (boundaries between klystron drives), as controlled by an integer (NBRIDE) and non-integer (RBRIDE) input data. It also fixes the tank synchronous phase to high precision (.002 degrees), so that central orbit disturbances can be observed to this resolution.

Synchronizing data is passed from 'CAVGEN' to 'CAVDYN', by incorporating the tank pair [wout,phis] into the TRACEX data set for a tank element.In addition TRACEX must output its view of the beam energy, so that all system data sets trimmed by TRACEX contain TRACEX predictions of energy. This allows the designer to check for large z-plane disturbances, by inspecting the TRACEX energy predictions, before the next step of PIC simulations with CAVDYN.

(c) TRACEX data contamination.

File splicing utilities ,truncations and other processes have introduced subtle contaminations into the TRACEX system data sets, during the Fermilab Linac Upgrade project. These effects are monitored using the 'CAVDYN' synchronism and z-orbit displays.

Figures I and II show a typical z-plane orbit disturbance for two types of data contamination.

Any inconsistency in the 'tank' data set [tank dl,tank E0t,tank phis,no.of cells,tank Wsout] , will be picked up by the z-orbit monitor in CAVDYN.

The bridge coupler data [bridge length], inconsistencies will appear in the z-orbit display, with gross errors (departure from odd-integer cell length) producing flagged warnings in the system printouts.

All non-synchronous drifts, marking interdrive boundaries, must be specified by the user in the CAVDYN input. This is implemented by the 'KLY' input vector in CAVDYN, and ensures that the CAVGEN data ,which has the correct array of bridge couplers and non-synchronous drifts, is in agreement with the CAVDYN synchronism detection logic.

CAVDYN assumes a fixed periodic sequence exists within the data sets, described as:

q/2.q/2.{n1.variable drifts}.tank.{n2.variable drifts}.q/2.q/2....etc

This corresponds to a FODO quadrpole lattice, with all quadrupoles inputted as half-quads, so that the FODO cell boundaries are available explicitly, at the quad mid-planes. Special transport sections can be dummied in by using tank elements with E0t=0., as integer cell length drifts.

(d) Beam phase space ellisoids are converted from the TRACE3D formats, and generated as various 6-D populations, with 100% edges at the TRACE3D emmittance values. No gaussian beams have been implemented as yet.

(e) The concept of a central orbit monitor spans all three codes, in the design hierarchy. 'CAVDYN' reconstructs the 'ideal' central orbit contained in the TRACEX data set, as well as a 'noisy' (as-constructed) central orbit, containing all 'noise' components introduced during the tolerance studies allowed by CAVDYN. These 'noise' components are both radial and longitudinal disturbances which deflect the '6d' optical axis from the 'ideal' condition.

The 'ideal' central orbit is produced by a genlin function, (here: 'CAVGEN'). If all three code functions are internally self consistent, then any data set, trimmed or untrimmed, should recontruct at the 6d origin in 'CAVDYN'.

Departures of ideal CO from the 6-d origin imply:

a. A genlin code that uses a non-standard gap transformation, or that designs coupled cavity cell lengths with large tolerances in the tank pair [Wsout,phis]

b. TRACEX trimming of the linac system destroying the synchronization constraints.

c. user editing of data sets introducing contamination.

d. Deliberate user revisions of cavity operating phasors, typically arising after cell.length designs are fixed. This can arise from updated SUPERFISH runs, or knowledge of the 'real' phasor distributions in bench measurements, which reflect real cell-coupling, frequency offsets, and other non-ideal cavity effects.

Note that the PIC space charge forces are not included in both CO dynamics, so that fluctuations from these forces do not impair this useful auditing function.

System Tolerance Methods.

The Fermilab Upgrade 805 MHz linac, involves a bunch size matching transition section, to match the 116 Mev DTL linac beam to a 28 tank side coupled accelerating structure designed to produce a 400 Mev proton beam. Some tolerance results for the accelerating sub system are descibed below.

Seven klystron drives are used in the accelerating section. In addition, 7 girders are used to mount the cavity -quadrupole combinations to the beam axis, ie 4 tank -quadrupole sets per girder. These system features require knowledge of the effects of corrrelated errors on the beam, specifically, klystron drive errors, affecting 4 cavities per drive, cavity length errors, and transverse displacement errors affecting 4 quadrupole-and-cavity combinations placed on a single suuport girder.

'CAVDYN' allows two tolerance study modes to determine operating or construction tolerance windows.

a. Central Orbit Mode.

This tolerance mode involves Monte Carlo type runs with particle sets representing an ensemble of 'noisy' system CO's.System noise is introduced, into either, or both transverse and longitudinal dynamics and the resulting CO errors distributions are produced .

These effects are termed 'linear',thouugh all non-linear dynamics are in force - but represent the local , 'linearized ' CO motions (6d) for small parameter variations. Large excursions of operating parameters can be invoked, to show phase space trajectories of the 'noisy' CO, to verify non-linear effects. Figures III and IV show a 400 Mev z-plane CO distribution for a single klystron drive phasor noise source (uniform: +/- [1.3 deg, 1% dg/g].)

Transverse motion of the central orbit can also be simulated from various correlated error distributions. These effects have been estimated from orbit theory (3), and have been checked for the cases of single and correlated (2 fodo periods) quadrupole misalignments.

b. Emittance Mode.

The second tolerance mode, carries the beam 6-d ellipsoid (with PIC space charge) through a user defined 'noisy' system,which has various correlated error distributions added to the system data set. This second tolerance mode is us used to verify emmitance growth effects from z-t coupling or other non-linear dynamics effects. The actual noise maps are presented graphically to aid the user in identifying the total system noise under investigation.

Sytem Noise Input.

Noise elements implemented in CAVDYN are:

: phasor errors (drive phase,drive gradient)
: cavity tranvserse displacements
: quadrupole transverse displacements
: girder transverse displacements
: tank length errors
: cell length errors
: bridge coupler length errors
: inputed central orbit offsets

Noise correlations are controlled by two integer vectors, that index the drive (Klystron) edges by cavity number, and the quadrpole and/or girder edges that define the grouping of quadrupole and cavity transverse displacement errors.

Summary:

Coupled cavity linacs can be synthesized, (CAVGEN)from the rf structure modelling predictions (SUPERFISH,MAFIA),of cavity fields. The synthesized linacs are expressed as TRACE3D data sets, which can be used for linear 3-d matching (with space charge) and the resulting matched systems (TRACE3D output data sets), can be

used for PIC non-linear dynamic simulations. All synchronization constraints are passed from synthesis to full dynamics testing, allowing central orbit detection of data contamination. In addition, full linac tolerance testing is supported using various modes of noise analysis, implemented in the CAVDYN code.

Future developemnt of the code is planned to incorporate:

a. non-ideal cavity phasor distributions, implied from as built cavity/coupler data.

b. Optimization of tune up procedures,such as the DELTA-T method, to detect nominal operating points.

c. cavity e-field radial dependencies from SUPERFISH modelling.

d. higher order gap transformations.

References.

1. Original Los Alamos coupled cavity codes were DESIGN and LINAC, written by K.Crandall, at LASL. Both CAVGEN and CAVDYN have

evolved from these 'seed' codes.
TRACEX,(FERMILAB UPGRADE)is a modified version of TRACE3D, that passes synchronization data, for Central Orbit reconstruction, to the PIC (non-linear dynamics) code.
TRACE3D is also a LASL code, written by K.Crandall.

2. Particle Accelerators.Vol.24.(1989) pp125. INR paper by Senichev and Shaposhnikova.(Moscow,USSR) on recent Soviet coupled cavity linac simulati ons.

3. Fred Mills, private communication. (Linac upgrade memo nov.11.88) 'Quad and Cavity Position Tolerances'.

Author's Address: Les. W. Oleksiuk.

Fermilab, MS307
Accelerator Division,
P.O. Box 500, Batavia Ill.
60510.

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FIGURE IA. LINAC CENTRAL ORBIT ERROR FROM 'EZ' ERROR.

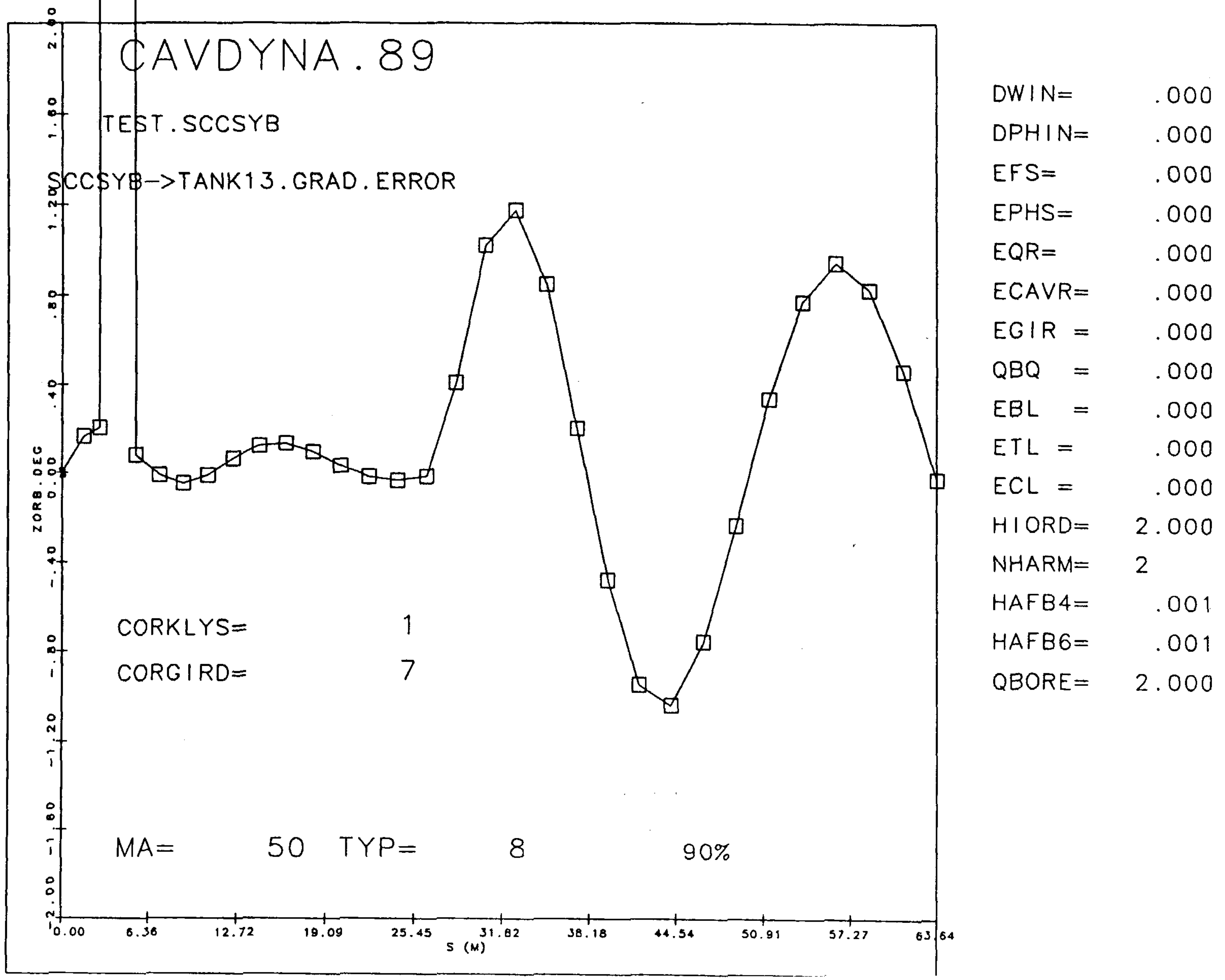


FIGURE IB. LINAC CENTRAL ORBIT ERROR - ENERGY EXCURSION.

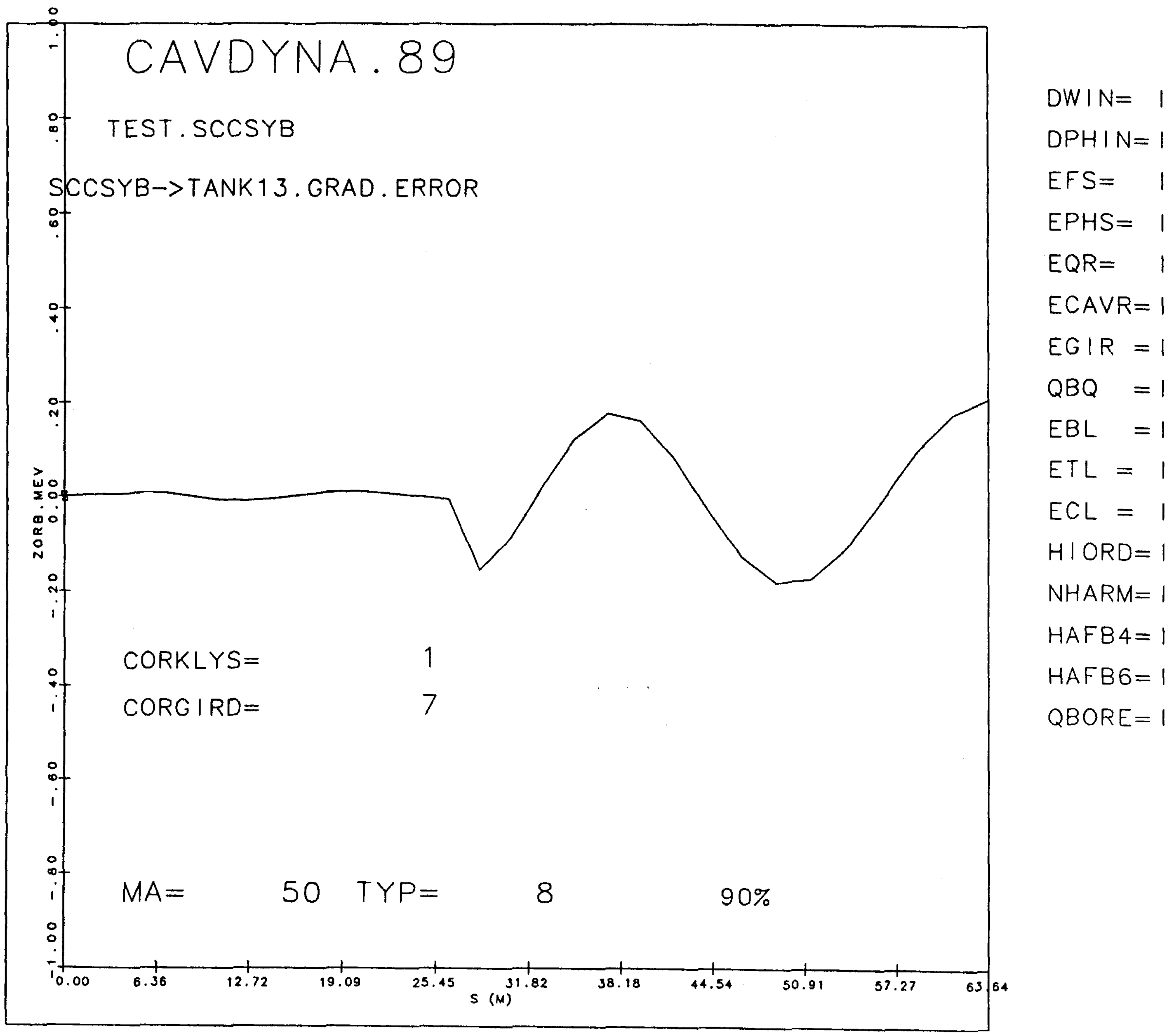


FIGURE IIA. LINAC CENTRAL ORBIT ERROR FROM BRIDGE COUPLER ERROR.

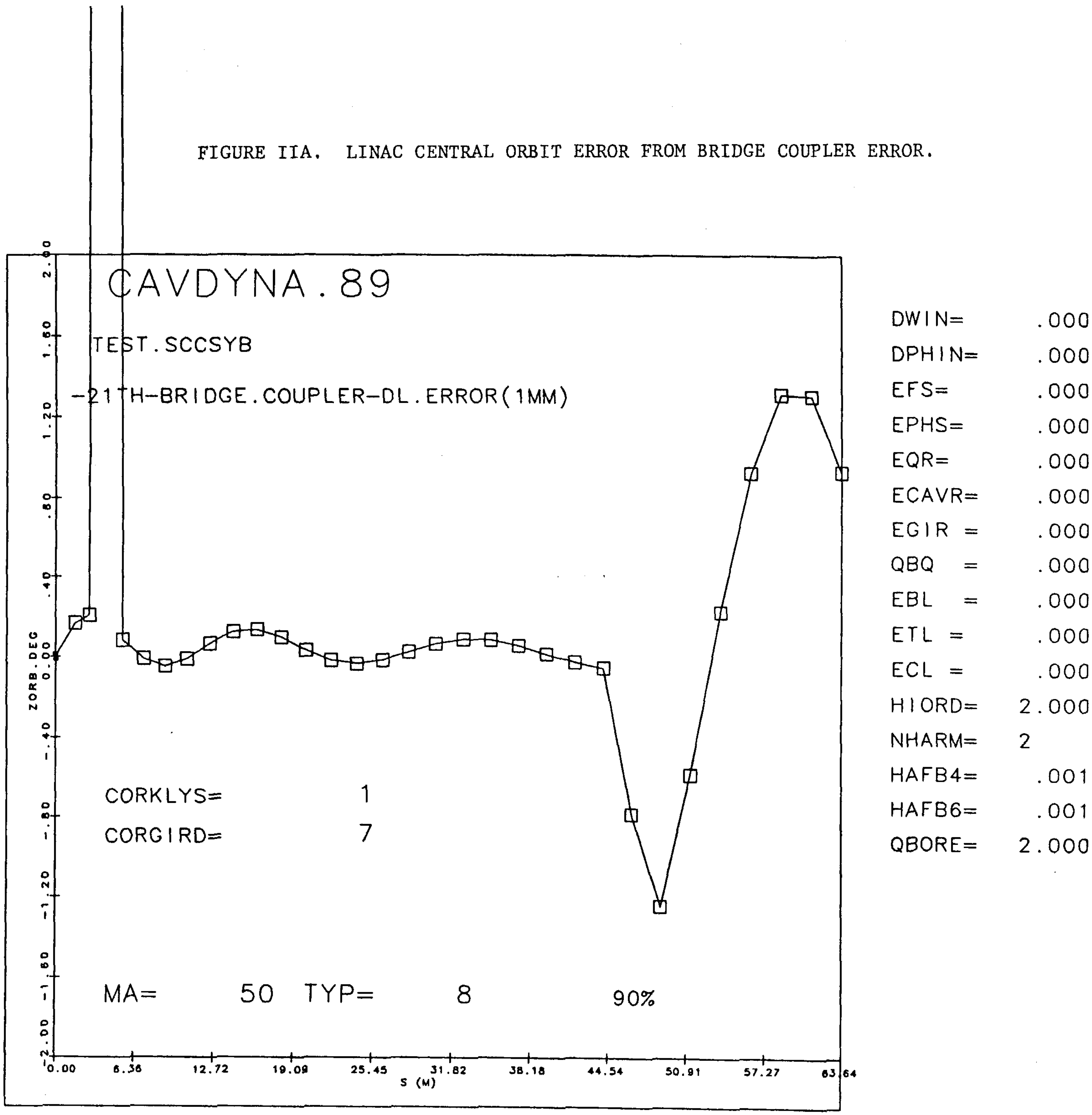
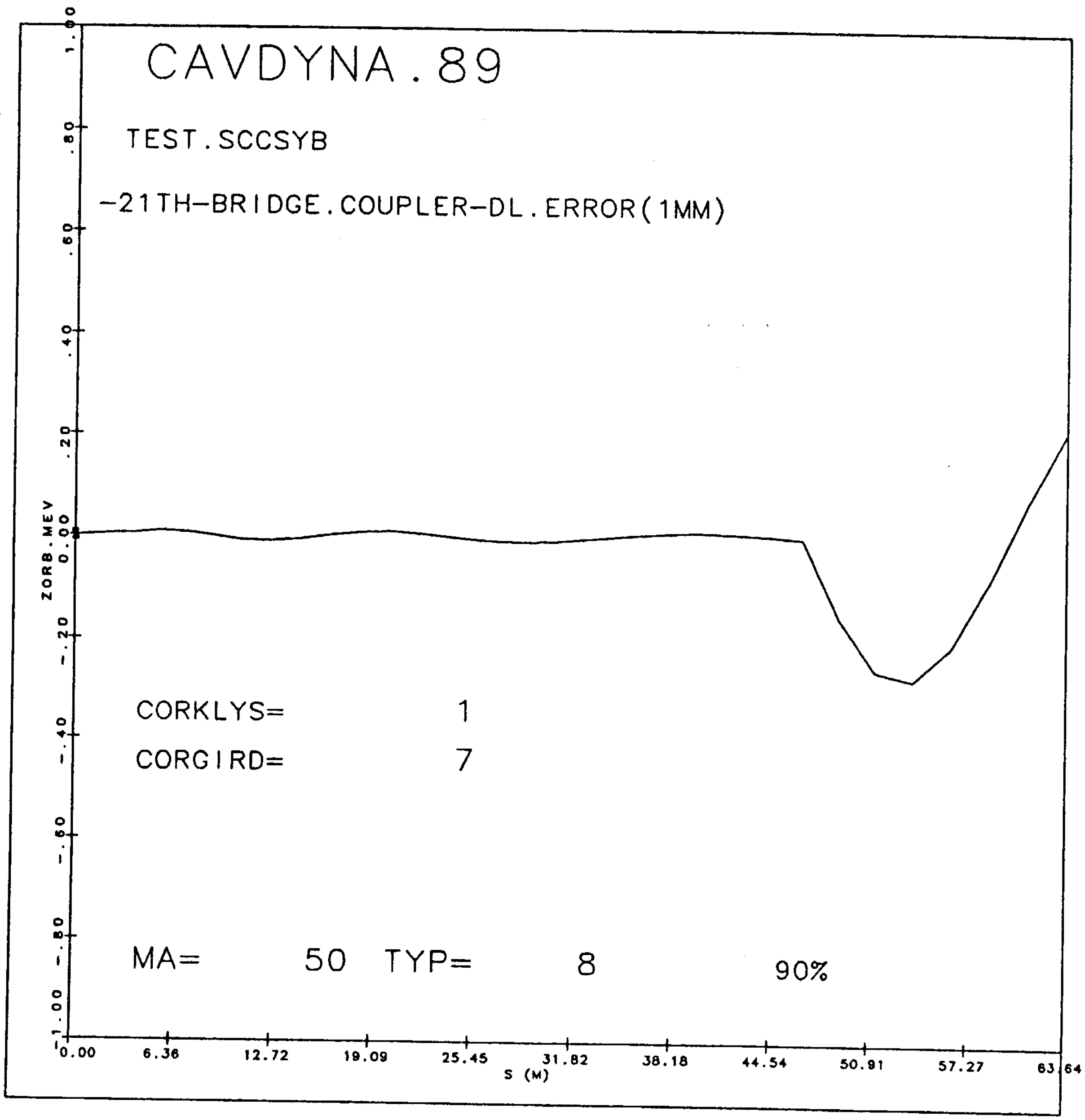


FIGURE IIB. LINAC CENTRAL ORBIT ENERGY EXCURSION.



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DPHIN= .000
EFS= .000
EPHS= .000
EQR= .000
ECAVR= .000
EGIR = .000
QBQ = .000
EBL = .000
ETL = .000
ECL = .000
HIORD= 2.000
NHARM= 2
HAFB4= .001
HAFB6= .001
QBORE= 2.000

FIGURE IIIA. RMS ENVELOPE OF CENTRAL ORBIT EXCURSION (PHASOR NOISE +1.3 deg/% RMS)

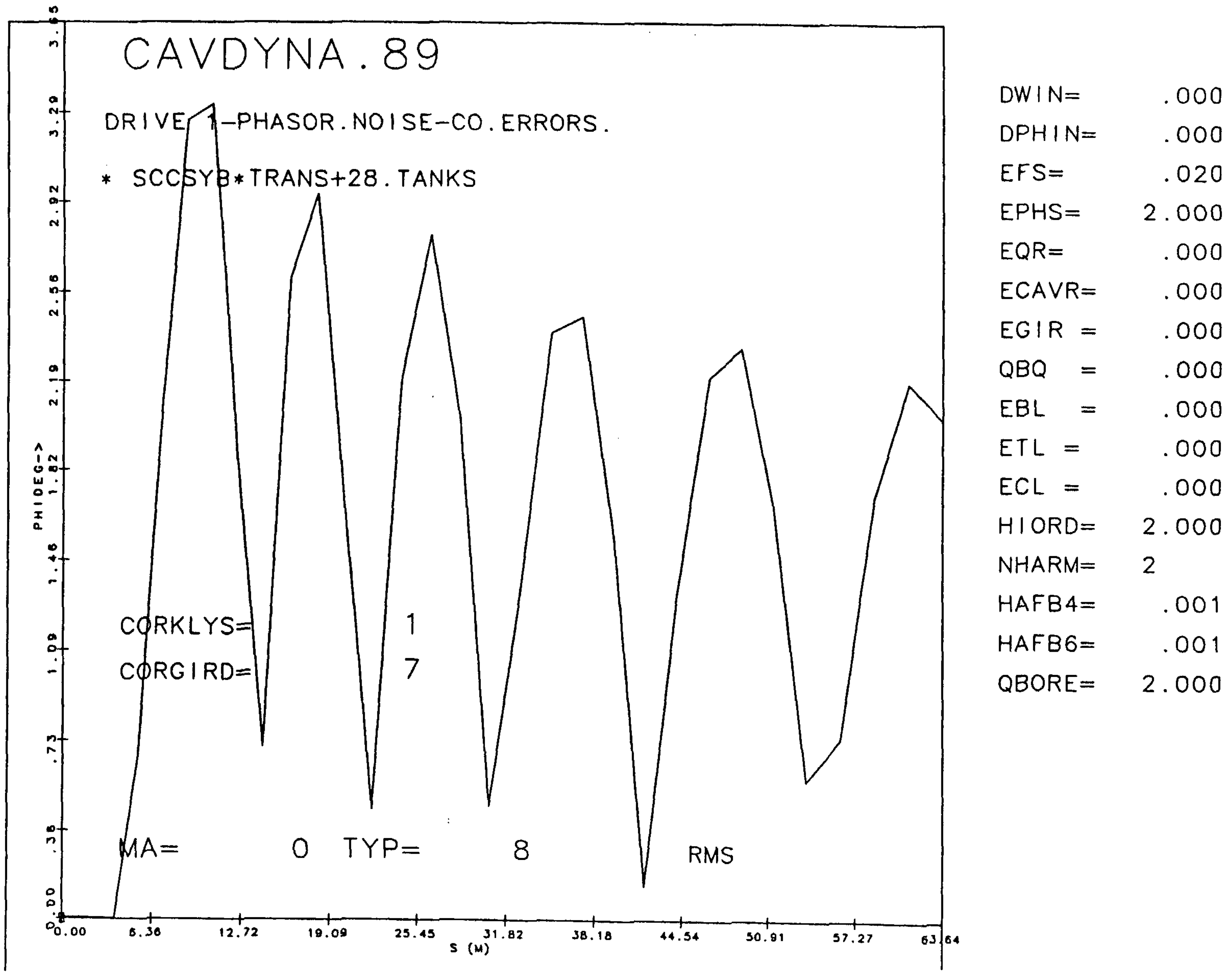
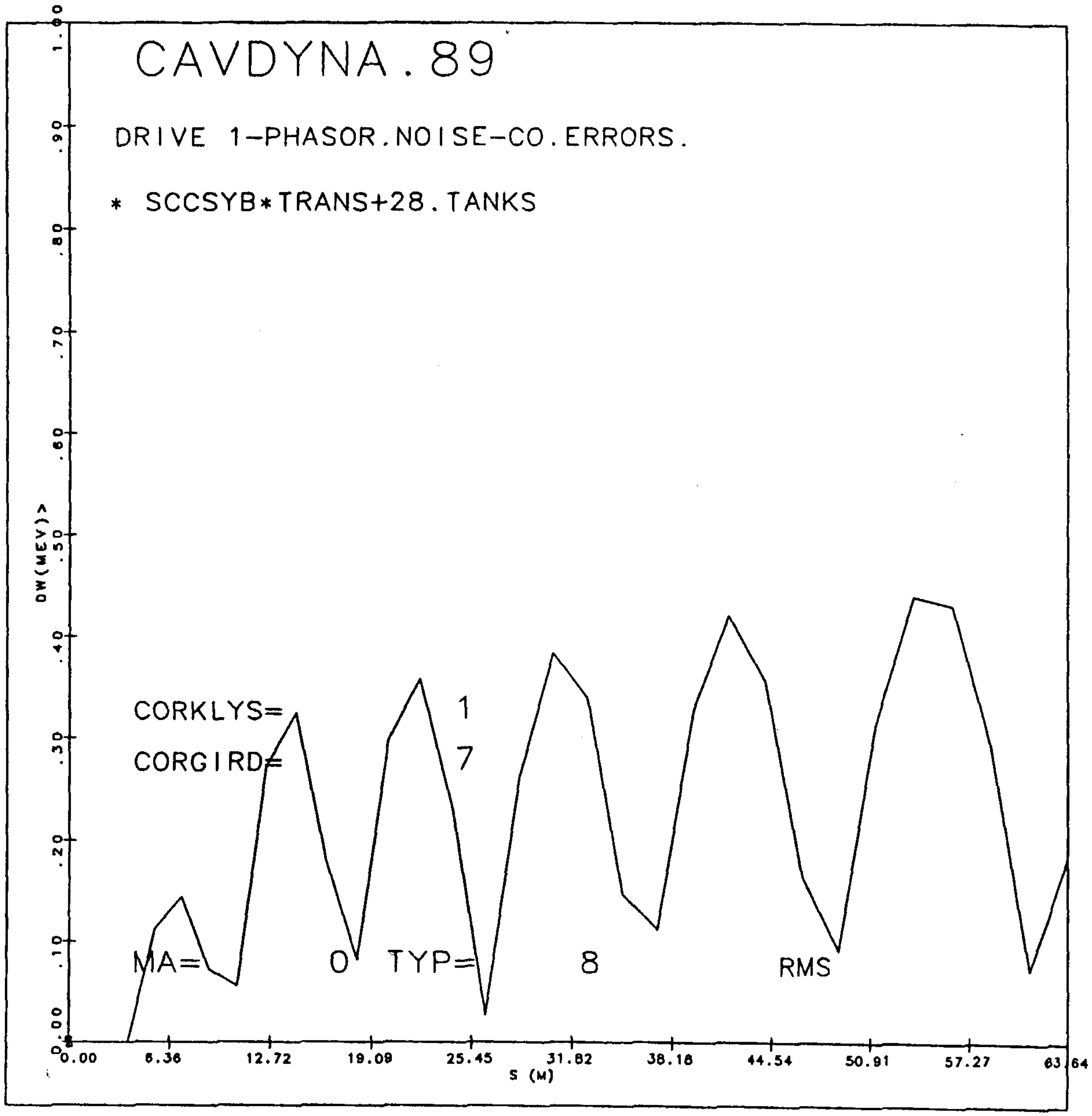


FIGURE IIIB. RMS ENVELOPE OF CENTRAL ORBIT EXCURSION (MEV)
1st DRIVE PHASOR NOISE = 1.3 deg + 1.3 % grad (RMS)



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EBL =	.000
ETL =	.000
ECL =	.000
HIORD=	2.000
NHARM=	2
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FIGURE IVB. PHASOR NOISE MAP _- TANKS 1 - 4 GRADIENT ERRORS.

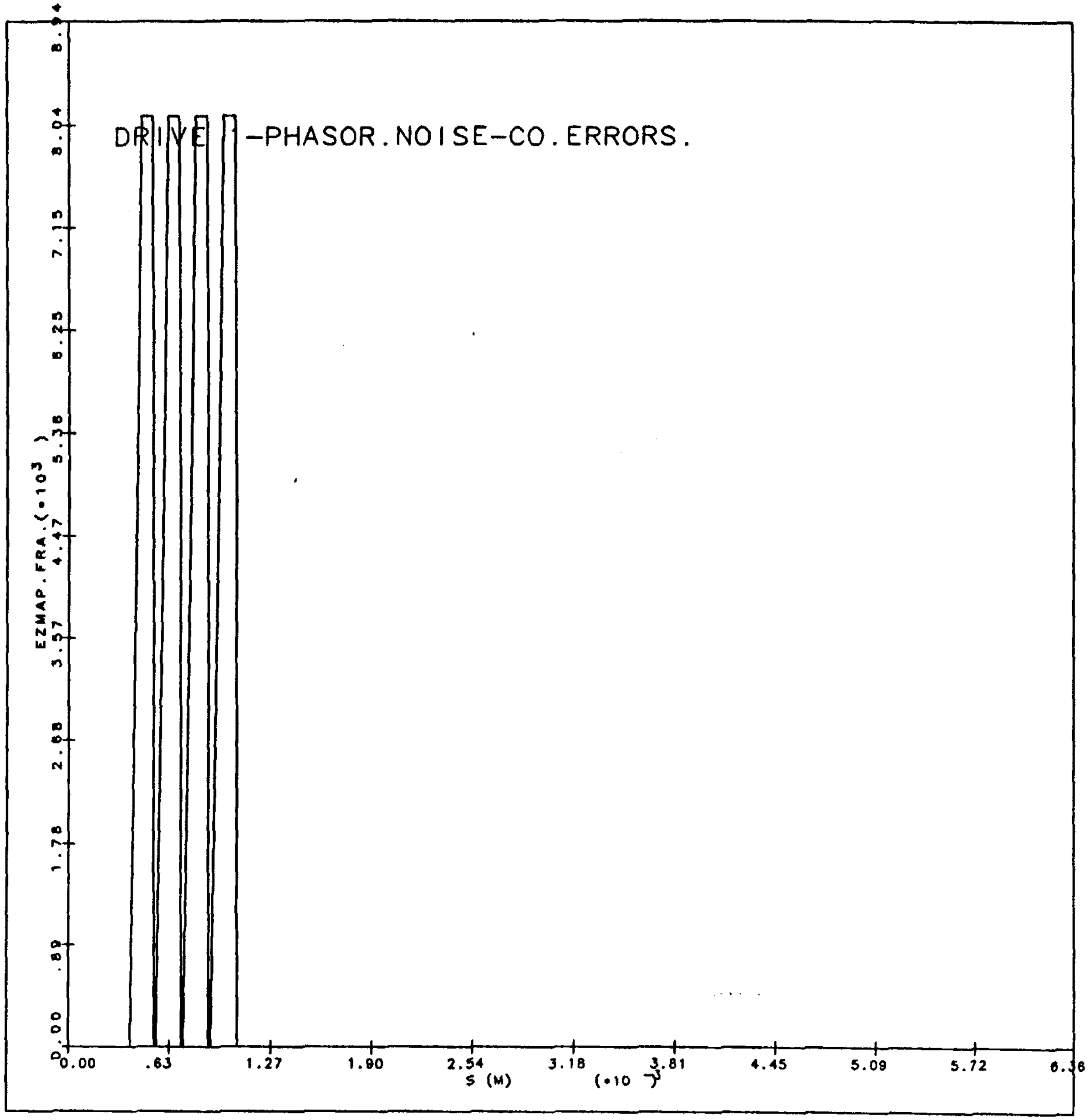

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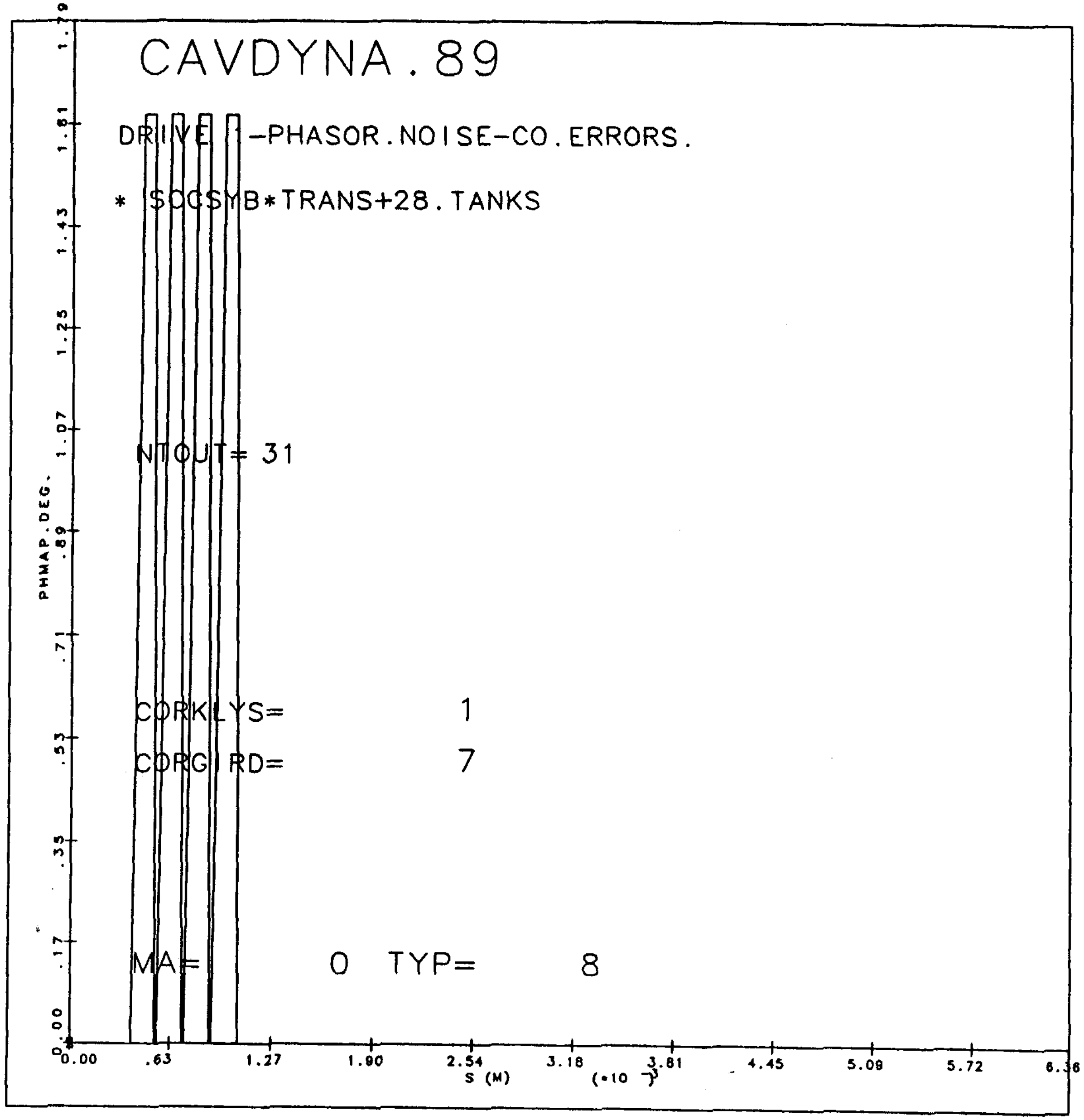
FIGURE IVA.   PHASOR NOISE MAP .TANKS 1 - 4 PHASE ERRORS.



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